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# Structural Health Monitoring Based Predictive Model of Concrete Bridge

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***Abstract*** – Reinforced concrete bridge is widely used nowadays in most modern small bridges because of *in situ* reinforced concrete construction which has the great advantage and simplicity. However, bridges possess high risk attack by corrosion by chloride ingress due to de-icing salt. The salt contains high level of chloride.The presence of chloride ions in concrete will cause corrosion initiation to reinforcement bar embedded inside the concrete. Thus, it will leads to severe structural damaged. Reinforced concrete bridge need to be managed effectively for better allocation of resources and serve based on it intended design. This paper reviews some chloride ingress prediction models and presents methodology for improving confidence in predicting corrosion initiation in reinforced concrete bridge.Uncertainty associated with material, environmental load and structural effects are considered before decision making by bridge owner. Hence the need for probabilistic analysis expressing life cycle performance in a reliability format. Probabilistic method can be used to deals with uncertainties exist. In this study, Fick's second law is used to mimic the chloride diffusion in concrete due to de-icing salt. This law takes initial values parameter as references to estimate future chloride content. Additional information through bridge inspection and monitoring will increase confidence in prediction model. Monte Carlo simulation is used to obtain parameters by repeating sampling method. Bayes' Theorem used to interpret the parameters into Fick's second law together with the experimental data to update future condition and performance of the bridge. The application of Bayes' Theorem is shown to significance improved confidence in predicting future condition and performance of concrete bridge under the chloride ingress. Thus, action plan may be performs with the help of the model in order to effectively managed and maintained the bridge.

***Keywords*:** Reinforced concrete bridge, corrosion, chloride ingress, Monte- Carlo, Bayes' Theorem,

## 1. Introduction

Concrete bridge is one of the structures which possess high risk in deterioration in term of corrosion due to the presence of acidity (chloride ion, sulphate ion and etc.) and humidity at the surrounding of the structure. Chloride ingress is one of the issues to cause the failure of reinforcement concrete. Omar (2002) said that majority of bridge in Malaysia are concrete, cracking and spalling of concrete are the most common in Malaysia.

In European countries, the corrosion induced majority cause chloride ingress due de-icing salt during winter time. Bastidas (2010) said that the corrosion which induces by chloride ion has become a critical issue for most of the reinforced concrete structure especially concrete bridge. Vladimir (2003) reported that the corrosion if reinforcement concrete will start to occur if chloride are pass through the protective film which exist on the surface of steel bar. This will easy to happen as the steel bar surrounded by high acidic environment.

Structural Health Monitoring System has been actively developed recently in order to monitor the healthiest of a bridge in particular for corrosion monitoring. The problem arise is the cost effectiveness of these and other measures is often unclear. Uncertainty associated with material, environmental load and structural effects are considered before decision making by bridge owner. Hence the need for probabilistic analysis expressing life cycle performance in reliability format (Stewart & Melchers, 1998). Probabilistic method can be used to deal with uncertainty exists.

The Fick's second law is selected to be used in this study to produce the predictive model. The reason is the chloride ingress happen due to the diffusion of chloride ion from the sea water into concrete bridge. In order to produce the predictive model that shown the probability of failure of the concrete bridge, the theory of safety and reliable of structure has been studied. According to the theory of safety and reliable, the structure will fail if the load more than the resistance. In this project, threshold of chloride concentration act as resistance while chloride concentration at given time and depth play a role as load. On the other hand, the corrosion will started in the concrete bridge if the chloride concentration at given time and depth more than the value of the threshold chloride concentration of the concrete bridge (Chateauneuf, 2010). The parameters that required producing the predictive model are surface chloride concentration, diffusion coefficient, time, depth of cover and threshold chloride concentration.

The Monte Carlo simulation method is using to simulate the random variable of the input data. By using this method, the probability of failure of the concrete bridge may able to be produced and called prior distribution. In order to make the simulation with higher efficiency, Latin Hypercube Sampling method was introduced in this project. The sampling method makes the distribution equally from the beginning to the end of the model. The uncertainty of the prior distribution should be reduced to ensure the accuracy of the model. Bayesian updating method was introduced and studied in this chapter in order to understand the method to update the prior distribution to posterior distribution. Likelihood is a function that required updating the prior distribution to posterior distribution by incorporating the likelihood function into prior distribution. The posterior distribution produced is more accurate compared to prior distribution.

## 2. Background

Chloride ingress is considered as a diffusion problem, the concentration of chloride throughout the concrete is estimated by analytically method (Bastidas, 2010). However, the analytical solution of the diffusion equation only valid for the saturated reinforcement structure which expose to the environmental that consist of constant concentration of chloride. But, this condition only exists in the submerged zone. There are other analytical solution under the Fick's Second Law called HETEK model were solved the shortcoming of the diffusion solution. HETEK model consider the time- dependency and the diffusion coefficient.

Models based on the theory of diffusion have been developed to best represent the chloride ingress in concrete and are widely used in practice to predict the initiation of reinforcement corrosion in concrete (Andrade et al. 1996). According to (Takewaka & Matsumoto, 1988) chloride penetration can be treated as diffusion process and seems to follow Fick's law of diffusion and they found that water cement ratio can give an effect to effective chloride diffusion coefficient. (Collepar.M, Turrizia.R et al. 1972) appears to be the first to apply Fick's second law to mimic chloride diffusion in concrete due to the de-icing salt. Work by Browne (1980) & Tuutti (1982) is also widely cited in this context. The model used for chloride ingress due to de-icing salt is as follows:

$$C(x,t) = C_O \left\{1 - erf\left(\frac{x}{2\sqrt{D.t}}\right)\right\} \tag{1}$$

## 3. Probabilistic Modelling and Simulation

The use of probabilistic model to handle the uncertainty present in the deterioration variable is increasing recently. Thoft-Christensen (1998) and Sorensen & Engulend (1996) are considered to be the first to use a probabilistic framework for corrosion initiation and propagation at rebar level. Then, a few researchers such as Stewart & Rowosky (1998) and Vu & Stewart (2000) have used probabilistic model to predict the bridge performance under chloride attack. Computing time dependent reliabilities analysis which is involved the development of probabilistic, behaviour based corrosion initiation and propagation (rate) models.

Duprat (2007) has proposed an assessment of reliability of reinforced concrete beam based on computation of reliability index and conclude that the corroded reinforcement has an effect on reliability of exposure condition, quality of concrete and design option.Estes, Frangopol et al.( 2003) have suggested that reliability analysis need to be updated based on results of inspections to forecast life-cycle performance as reliability methods have gained increasingly with advanced techniques on health monitoring system, the uncertainty in the result can be reduced.

Bayesian approach has been used by a large number of researchers to update information in order to reduce uncertainty. Faber & Sorenson (2001 & 2002) have used this methodology to update the information regarding the attainment of defined condition states at a given time which is capable of incorporating formally the uncertainty associated with instrument or measurement with updating framework. Bayesian approach also has been used by Rafiq et al, (2005) for performance updating of deterioration of concrete bridges fitted with a proactive health monitoring

### 3. 1. Probabilistic Modelling of Deterioration due to Chloride Ingress

Field and laboratory testing along with health monitoring system can be used to identify deterioration on the bridge. In particular, chloride profile generally tested in the laboratory to establish the concentration of chloride in the concrete samples. The effective diffusion coefficient and surface chloride concentration are derived by using non-linear regression analysis to fit the profiles to the diffusion based deterioration model. Stochastic models presented by Engelund & Sorensen (1998) for variables of deterioration such as threshold chloride concentration, cover thickness, surface chloride concentration and propagation of corrosion. In this section, the characteristic of these variables in the deterioration model are presented.

### 3. 2. Updating Model for Chloride Induced Deterioration

The objective of Bayesian updating procedure is to reduce the uncertainty (i.e. COV) in the predictive performance (Rafiq, 2004). In this case, uncertainty in the probability of chloride concentration at given depth and cumulative time exceeds the threshold chloride concentration. Collepardi et al (1997) who first to apply a model used to mimic chloride diffusion in concrete.

### 3. 3. Simulation of Probabilistic Performance Prediction

In this study, Monte Carlo Simulation with Latin Hypercube Sampling is used to estimate prior and posterior performance prediction of chloride concentration. The output of this simulation is in the form of probability density function of prior, likelihood and posterior distributions. The probability of corrosion initiation for a given time (e.g. 20 years in this case) also presented.

Table. 1. Summary of parameters involved in chloride ingress model

| Parameter | Mean | C.O.V | Distribution | Reference |
|---|---|---|---|---|
| $C_o$ | 3.5 kg/m$^3$ | 0.5 | Lognormal | Vu & Stewart (2000) |
| *D (Nominal)* | 5x10$^{-5}$m$^2$/yr | | | Vu & Stewart (2000) |
| *Model Error (D)* | 1.0 | 0.2 | Normal | Vu & Stewart (2000) |
| *Cth* | 0.9 kg/m$^3$ | 0.19 | Uniform (0.6-1.2 kg/m$^3$) | |
| *Xc* | 40 mm | 0.1 | Normal | Chryssanthopoulos & Sterrit (2002) |

## 4. Result and Discussion

In order to evaluate the chloride concentration at given time and depth, all the generated data should input into equation 3. The prior probability of failure is determined based on previous inspection data. The prior distribution of probability of failure was obtained by using following equation:

$$P(Failure) = \frac{\mathrm{C(x,t)} > 0}{Total\ Number\ of\ \mathrm{C(x,t)}} \quad (5)$$

The prior distribution may be updated to posterior distribution by using Bayesian updating. If a prior distribution $\theta \sim N(\theta_0, \sigma_0^{-2})$, the posterior distribution may write as $\theta \sim N(\bar{\theta}, \sigma^{-2})$. The likelihood function may obtain based on the data from the sensor and incorporating into prior distribution. In this study, the likelihood function is decreasing 50% from the prior distribution. These procedures were repeated for 20 times to obtain the probability of failure for 20 years. The probability density function for prior, posterior and likelihood of chloride concentration at year 20 was plotted at the end of the procedure.

Bayesian inference is important in updating the existing predictive model. The likelihood function is the important element to update the prior distribution to posterior distribution. Ronquisk (2005) said that the likelihood should be used to update the prior distribution to posterior distribution to ensure the probability distribution become believable after incorporating new data. Figure 1 below describes the prior, posterior and likehood distribution of chloride concentration which is generated by using likelihood function that 50% less than the prior mean and standard deviation, the posterior distribution that produced is shift to the left from the prior distribution.

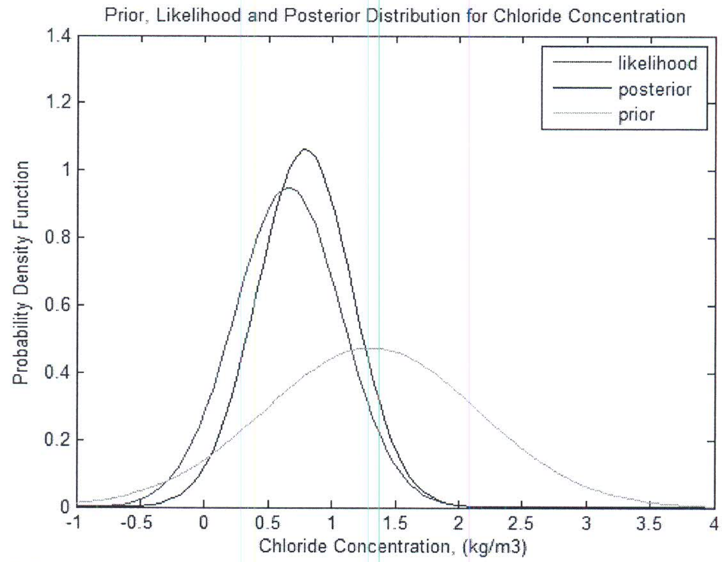

Fig.1. PDF for prior, likelihood and posterior distribution for chloride concentration

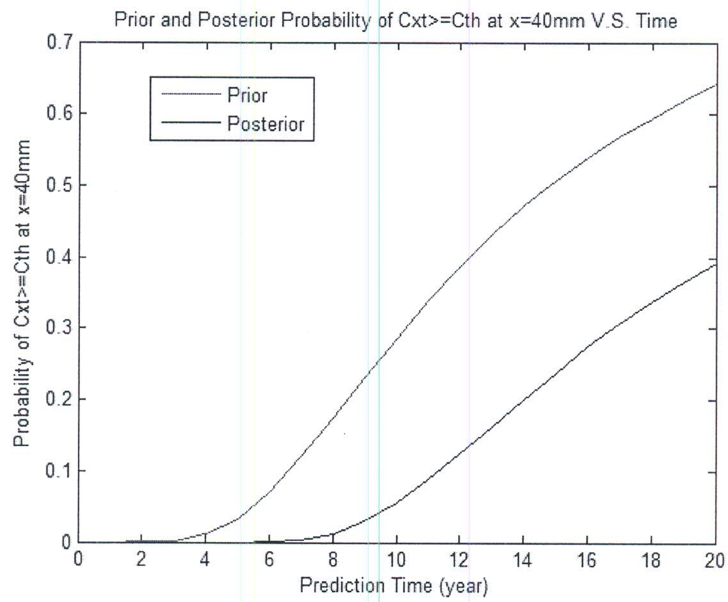

Fig.2. Point in time probability of failure for chloride concentration

Based on Figure 2, it is observed that the probability of failure for prior is higher than that of posterior at year 20. The probability of failure for prior is 0.65 and 0.4 for posterior. By observing the increasing and decreasing of likelihood function, it is shown that the likelihood function is very influencing the predictive model. By incorporating a new data, the reliability of the result has been improved. As the accurate predictive model able to be produced, the service life of the structure able to be predicted more accurately. Thus, lower cost used for maintenance of the structure as the time at which the corrosion will be started able to be predicted.

### 4. 1. Exposure Condition

Exposure condition is one of the important elements that influencing the model. As the bridge structure is directly contact with salt, surface chloride concentration becomes the dominant in predictive model. The different surface chloride concentration will give the different probability of failure. Table 2 shown the model of surface chloride concentration produced by previous researcher:

Table. 2. Model of surface chloride concentration

| Researcher | Type | Mean | Standard Deviation |
|---|---|---|---|
| Thoft- Christensen et al (1996) | Normal | 3.24 | 0.22 |
| Vu & Stewart (2000) | Lognormal | 3.5 | 1.75 |
| Lounis & Amleh (2003) | Normal | 3.24 | 0.5 |

Figure 3 is the PDF graphs were produced by using the data above. It is observed that the different PDF for surface chloride concentration were produced by using the different model of surface chloride concentration. The lower value of the standard deviation will give the tighter distribution.

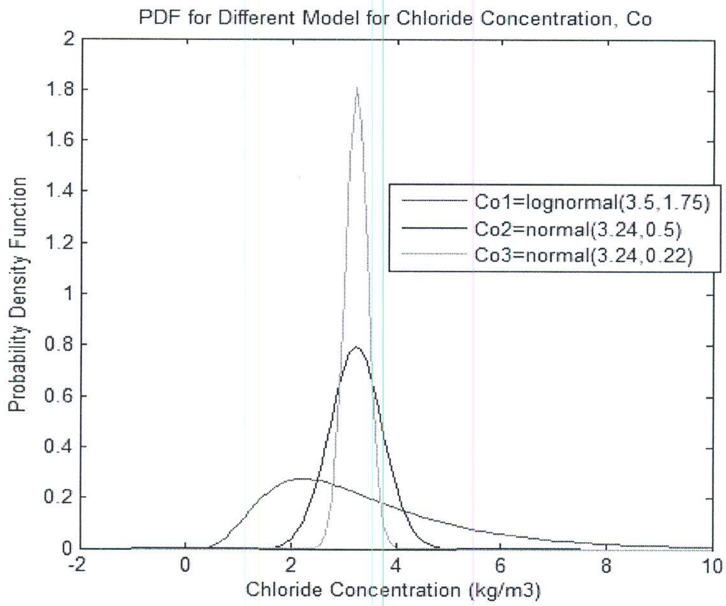


Fig.3. PDF for different model for chloride concentration

Figure 4 illustrated the prior and posterior probability of failure that influence by the different model of surface chloride concentration. Model of surface chloride concentration with the standard deviation of 0.5 show the higher probability of failure compare to the model with standard deviation of 0.22. Also, the model of surface chloride concentration with the value of standard deviation of 1.75 showed the highest probability failure for posterior distribution. For prior distribution, there are same probabilities of failure for all of the three distributions at year 13. After year 13, the probability of model with standard deviation of 1.75 shown the lowest probability of failure followed by model with standard deviation of 0.5 and 0.22.

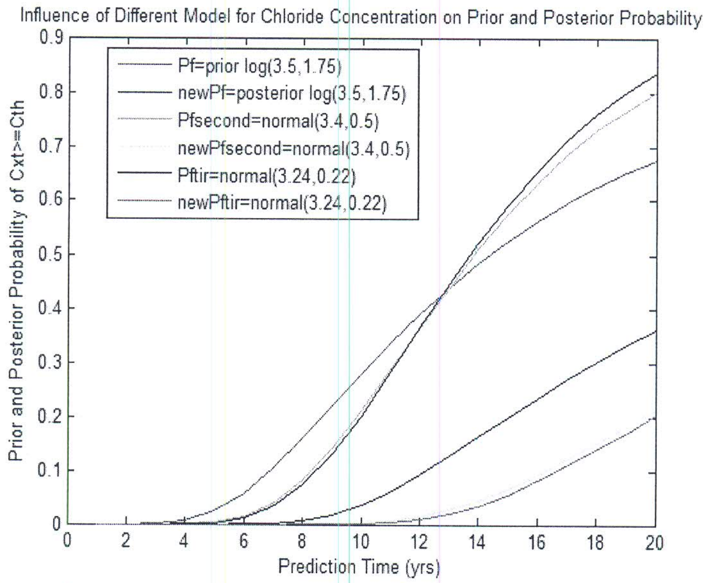

Fig.4. Influence of different model for chloride concentration

The exposure condition of the structure should determine carefully in order to make the predictive model accurate to avoid the underestimate or overestimate the initiation of corrosion. Thus, by produce a more accurately predictive model, the cost and time used to maintenance may able to be saved as the predictive model able to show the time at which the corrosion started.

### 4. 2. Cover Depth

Concrete cover is an important component that used to protect the steel inside the structure. The suitable cover depth should be used to ensure the protection is enough provided. Quality of concrete cover is affect by the workmanship and the materials used. According to Harrison (2003), the quality of concrete cover strongly affect by materials and workmanship. The low quality of materials produces low quality of concrete cover. The poor workmanship will also produce low quality of concrete cover as the worker lack of knowledge in handling concrete. Sterrit(2000) has categorized the quality of concrete into 'Good Quality', 'Average Quality', and 'Poor Quality'.

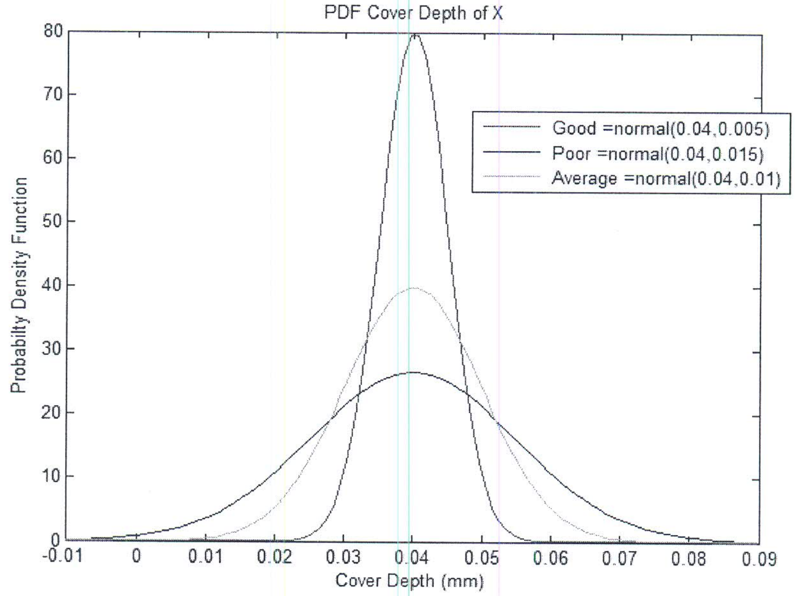


Fig.5. PDF for three categories of cover depth

Figure 5 illustrated the probability Density Function for the three categories of the cover depth. The good quality of cover depth with the standard deviation of 0.005 give a tighter distribution compare to the poor distribution with standard deviation with 0.015.

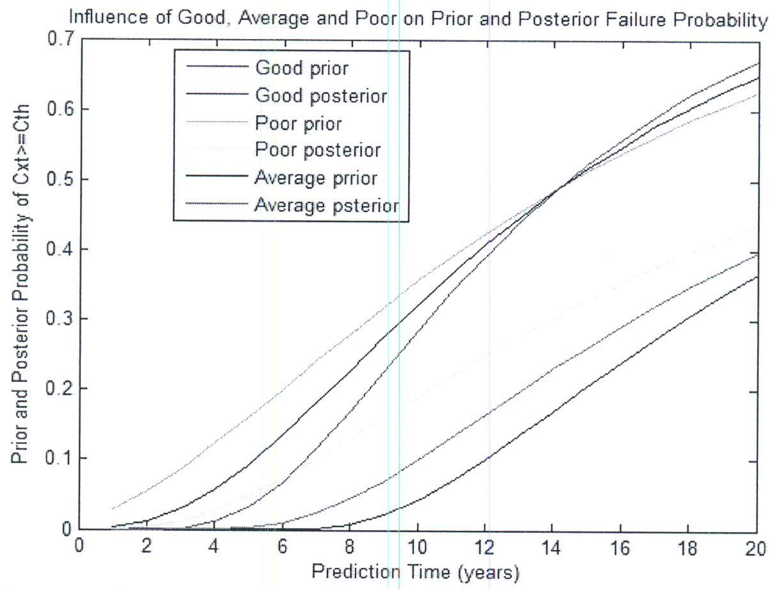


Fig.6. Influence of good, average and poor on prior and posterior failure probability

According to Figure 6, there are same probabilities of failure for all of the three distributions at year 14 for prior distribution. After the prior distribution updated to posterior distribution which is more accurate, it is shown that the poor quality cover contribute highest probability of failure. However the good quality covers showed the lowest probability of failure. Thus, in order to make the structure with longer service life, the workmanship and the materials used should be guarded carefully.

## 4. Conclusion

Probabilistic modelling with various parameters defined as variables is presented and the prior model is based on these parameters. Bayesian theory is applied to formulate the updating with incorporating new data into the prior model to determine the probability of failure. The accuracy of the posterior distribution was proved by the shape of the distribution shown in the probability density function. The tighter distribution, the lower value of mean and standard deviation, the more accurate predictive model produced. It is also prove that, the more accurate model will represent the lower probability of failure. Conceptually, data used to produce likelihood function is obtained from health monitoring system. By health monitoring system installed in a structure and regular inspection, the efficiency of long term performance prediction can be increased.The likelihood distribution is incorporating into the prior distribution to produce posterior distribution. From the result, it has shown that by using Bayesian theory, uncertainty of the posterior model will be reduced hence increased confidence in predicting future performance. The predictive model has been generated and the service life and service period able to be determined from the model which can help the bridge owner to effectively plan for bridge maintenance.

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